



Development and Testing of a Resonance Source Gas Filter Correlation Spectrometer

C. J. Fisher and R. J. Bryson
ARO, Inc.

May 1980

Final Report for Period August — September 1979

Approved for public release; distribution unlimited.

AEDC TECHNICAL LIBRARY



5 0720 00034 4384

**ARNOLD ENGINEERING DEVELOPMENT CENTER
ARNOLD AIR FORCE STATION, TENNESSEE
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE**

NOTICES

When U. S. Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

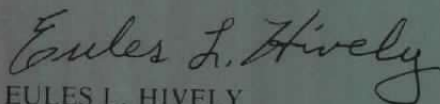
Qualified users may obtain copies of this report from the Defense Technical Information Center.

References to named commercial products in this report are not to be considered in any sense as an indorsement of the product by the United States Air Force or the Government.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

APPROVAL STATEMENT

This report has been reviewed and approved.



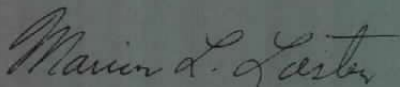
EULES L. HIVELY

Project Manager

Directorate of Technology

Approved for publication:

FOR THE COMMANDER



MARION L. LASTER

Director of Technology

Deputy for Operations

UNCLASSIFIED

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM										
1 REPORT NUMBER AEDC-TR-79-98	2 GOVT ACCESSION NO	3 RECIPIENT'S CATALOG NUMBER										
4 TITLE (and Subtitle) DEVELOPMENT AND TESTING OF A RESONANCE SOURCE GAS FILTER CORRELATION SPECTROMETER		5 TYPE OF REPORT & PERIOD COVERED Final Report, August - September 1979										
7 AUTHOR(s) C. J. Fisher and R. J. Bryson, ARO, Inc., a Sverdrup Corporation Company		6 PERFORMING ORG REPORT NUMBER										
9 PERFORMING ORGANIZATION NAME AND ADDRESS Arnold Engineering Development Center/DOT Air Force Systems Command Arnold Air Force Station, Tennessee 37389		8 CONTRACT OR GRANT NUMBER(s)										
11 CONTROLLING OFFICE NAME AND ADDRESS Arnold Engineering Development Center/DOS Air Force Systems Command Arnold Air Force Station, Tennessee 37389		10 PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 65807F										
14 MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12 REPORT DATE May 1980										
		13 NUMBER OF PAGES 24										
		15 SECURITY CLASS (of this report) UNCLASSIFIED										
		15a DECLASSIFICATION DOWNGRADING SCHEDULE N/A										
16 DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.												
17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)												
18 SUPPLEMENTARY NOTES Available in Defense Technical Information Center (DTIC)												
19 KEY WORDS (Continue on reverse side if necessary and identify by block number) <table style="width: 100%; border: none;"> <tr> <td style="width: 50%;">test methods</td> <td>carbon monoxide</td> </tr> <tr> <td>resonance</td> <td>measurement</td> </tr> <tr> <td>source</td> <td>high temperature</td> </tr> <tr> <td>gas filters</td> <td>combustion</td> </tr> <tr> <td>spectrometers</td> <td>jet engine exhaust</td> </tr> </table>			test methods	carbon monoxide	resonance	measurement	source	high temperature	gas filters	combustion	spectrometers	jet engine exhaust
test methods	carbon monoxide											
resonance	measurement											
source	high temperature											
gas filters	combustion											
spectrometers	jet engine exhaust											
20 ABSTRACT (Continue on reverse side if necessary and identify by block number) The development and testing of a resonance source gas filter correlation spectrometer for carbon monoxide concentration measurement in high temperature, possibly acoustically and optically noisy combustion systems are described. The instrument incorporates a microwave-excited, low-pressure carbon monoxide plasma radiation source. The operation, calibration, and												

UNCLASSIFIED

UNCLASSIFIED

20. ABSTRACT (Continued)

modeling of the instrument response as well as application to the measurement of CO concentration in the exhaust of a jet engine combustor are described. The report concludes with suggestions for the further use and development of the instrument.

PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC). The results of the research were obtained by ARO, Inc., AEDC Division (a Sverdrup Corporation Company), operating contractor for the AEDC, AFSC, Arnold Air Force Station, Tennessee, under ARO Project No. P321-14. The Air Force project manager was E. L. Hively, DOT. The data analysis was completed on September 15, 1979, and the manuscript was submitted for publication on November 21, 1979.

The resonance source gas filter correlation spectrometer design and a substantial portion of its construction were directed by Dr. B. Krakow before his departure from AEDC. His contributions are gratefully acknowledged.

CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	5
2.0 INSTRUMENT DESCRIPTION AND OPERATING PRINCIPLES AND PROCEDURES	
2.1 Instrument Description	6
2.2 Operating Principles	10
2.3 Operating Procedures	12
3.0 DEVELOPMENT AND CALIBRATION	14
4.0 PRELIMINARY MODEL OF THE INSTRUMENT RESPONSE	15
5.0 TEST CELL APPLICATION	19
6.0 CONSIDERATIONS FOR FUTURE INSTRUMENT DEVELOPMENT	21
7.0 SUMMARY AND CONCLUSIONS	22
REFERENCES	22

ILLUSTRATIONS

Figure

1. RSGFC Spectrometer Transmitter Unit	6
2. RSGFC Spectrometer Receiver Unit	7
3. RSGFC Spectrometer Electronics Package	8
4. RSGFC Spectrometer Optical Schematic	9
5. RSGFC Spectrometer Source Spectrum - Pressure, 1.32 kPa; Input Power, 42 w	11
6. CO Fundamental Interference Filter Transmittance Plot	13
7. CO P Branch Interference Filter Transmittance Plot	14
8. RSGFC Spectrometer Test Cell Calibration*Curve - Path Length, 10 cm; Temperature, 300 K	17
9. Diagram of Research Cell R-2C-1	20

TABLES

1. RSGFC Spectrometer Laboratory Calibrations	16
2. Test Cell Results	20

1.0 INTRODUCTION

Concentration determinations of minor gaseous species in combustion systems have been traditionally accomplished with probe extraction techniques and conventional commercial gas analyzers. In recent years, the ability of probe sampling to preserve the chemical identity of the sampled gas has been seriously questioned (Refs. 1 and 2). In addition to this possible problem, physical limitations and material problems often render the use of probe technology impractical. For these reasons, there has been a great deal of interest in noninterference in situ optical techniques of combustion gas diagnostics.

Instruments designed for field use detection of minor gaseous species must be highly sensitive and specific to the species of interest and be relatively immune to the deleterious effects of acoustical and optical noise, degradation of exposed optical components, and particulate attenuation of signals. A resonance source gas filter correlation (RSGFC) spectrometer has been developed to meet these requirements for CO concentration determinations behind combustor and jet and rocket engines.

Gas filter correlation spectrometers have been developed for a variety of gaseous species measurement applications including gaseous pollutant measurements in automobile and jet engine exhausts (Refs. 3 and 4), smokestack gases (Ref. 5), and detection of gaseous atmospheric pollutants from high altitudes (Refs. 6 and 7). The common feature of these instruments is the correlation cell, a cell containing the gas of interest, which is periodically placed in the optical path. Typically, a single detector is employed which is alternately exposed to radiation which has passed through the correlation cell, the correlated radiation beam, and then to radiation which has not. The presence of the species of interest in the sample volume changes the ratio of the correlated to the noncorrelated radiation intensities. The use of the correlation cell in this arrangement provides a measure of discrimination against other species with overlapping spectra as well as continuum interferences. Other molecular spectra ("uncorrelated" spectra) and continuum interferences would be expected to affect the two beams proportional to their intensities and hence leave the intensity ratio unchanged.

The instrument described in this report is an absorption correlation spectrometer incorporating a narrow line CO resonance source. Narrow line resonance radiation is much more strongly absorbed than continuum radiation and hence is more suitable for applications for which high sensitivity is an important design criterion. A narrow line resonance source radiates primarily at absorption line centers and thus samples the absorption spectrum at the points of maximum absorption. The use of a narrow line resonance source provides the advantage of the large line center absorption coefficients seen

under very high resolution without the use of sophisticated and delicate high resolution instrumentation.

The goals of this project were to complete the development of the RSGFC spectrometer and test it in a research combustor test cell. These goals were accomplished. The balance of this report consists of a description of the instrument, an account of the development and calibration of the instrument, the development of a preliminary model of the instrument response, and a description of a test cell application and conclusions.

2.0 INSTRUMENT DESCRIPTION AND OPERATING PRINCIPLES AND PROCEDURES

2.1 INSTRUMENT DESCRIPTION

The RSGFC spectrometer consists of a transmitter unit, a receiver unit, an electronic signal processing package, and a gas handling system. Photographs of the instrument are presented in Figs. 1 to 3. An optical schematic is presented in Fig. 4. The transmitter and the receiver are mounted on 117- by 97- by 2.5-cm aluminum plates.

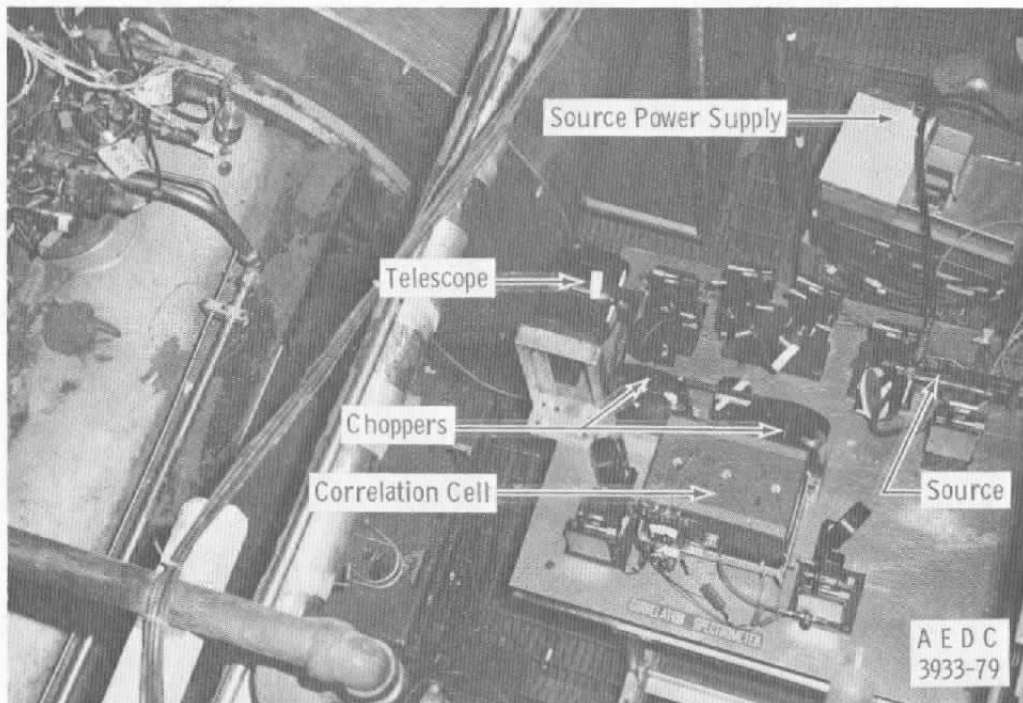


Figure 1. RSGFC spectrometer transmitter unit.

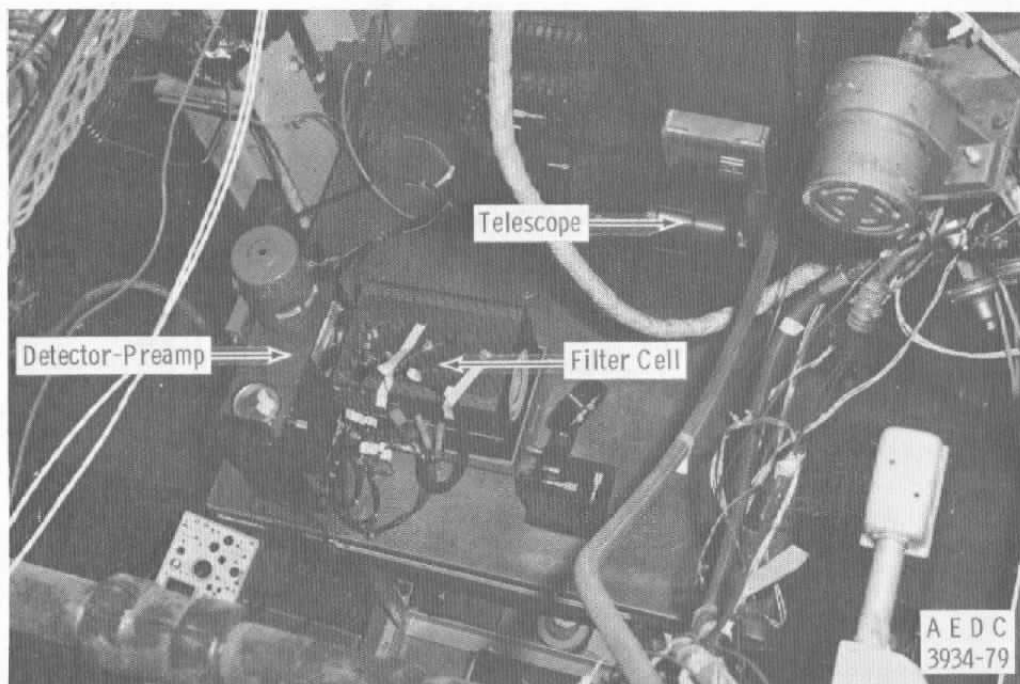


Figure 2. RSGFC spectrometer receiver unit.

All concave mirrors in both the transmitter and receiver units are identical gold-coated elliptical mirrors (M1 through M9 of Fig. 4). They are all mounted in optical orienting and translating holders equipped with five micrometer screw adjustments.

The transmitter source consists of a low-pressure flowing gas CO source tube with a microwave antenna powered by an 85-w, 2,450-MHz power supply. The source tube is a 12-mm-OD by 12-cm-long Pyrex® tube with gas intake and exhaust connections. It is equipped with a 2.5-cm-diam by 3-mm-thick calcium fluoride end window.

The source beam is focused by mirror M1 on one of two mirrored choppers (C1). When this chopper is open, the emerging beam is focused by mirror M3 at the center of the 10-cm-long by 7.5-cm-diam gas filter correlation cell. The cell, consisting of a copper body with 7.5-cm-diam by 6-mm-thick calcium fluoride windows, was filled with 720 torr of pure CO. The beam is then refocused by mirror M4 on the second mirrored chopper. When this chopper is open, the beam reaches mirror M6 which focuses the beam 3 cm in front of the entrance of the 15-cm-diam cassegrainian transmitting telescope. The beam following this route is designated the correlation cell beam.

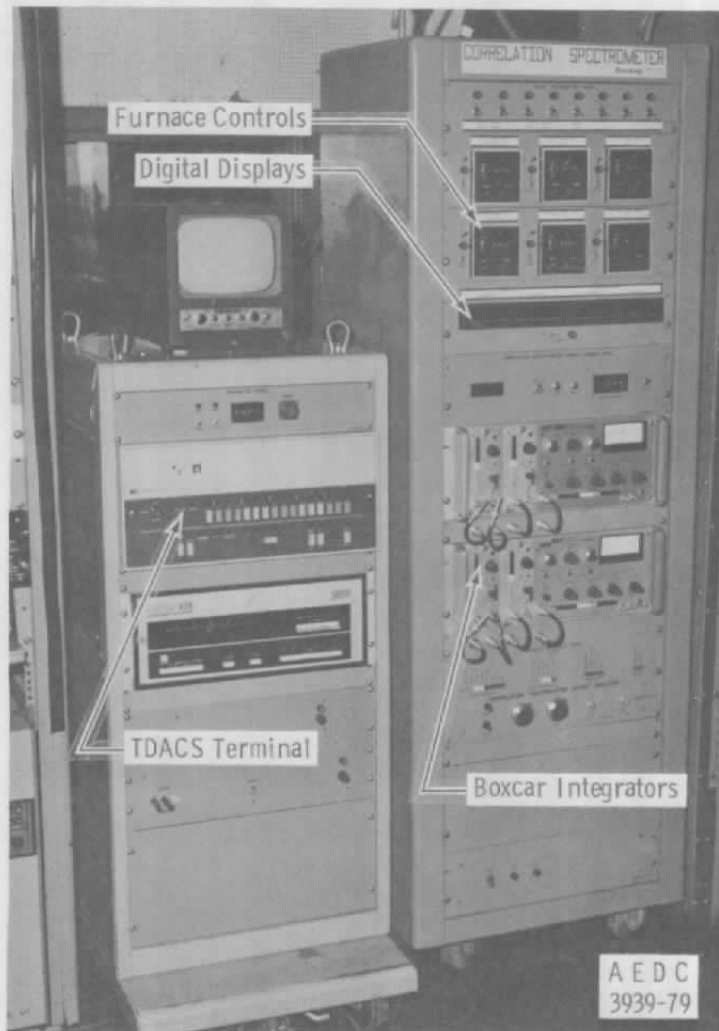


Figure 3. RSGFC spectrometer electronics package.

When the first chopper (C1) is closed, the source beam from mirror M1 is reflected by the chopper surface to mirror M2 which focuses the beam at a neutral density filter (NDF). The NDF consists of two 6-mm-thick by 2.5-cm-diam Irtran 2[®] optical flats selected to approximately match the intensity of the NDF beam to that of the correlation cell beam. The NDF beam is then focused by mirror M5 on the surface of the second chopper, C2. When this chopper is closed, the beam is reflected to mirror M6 which focuses it in front of the entrance of the transmitting telescope. The optical system was designed so that from the second chopper surface on, the two beams follow the same path, i.e., they are recombined at that point. When the first chopper is closed and the second open, or vice versa, neither beam reaches the transmitter telescope.

The two double-bladed choppers are synchronously driven by an electric motor at approximately 5,000 rpm by means of a timing belt-pulley system. The choppers are initially set 45 deg out of phase relative to each other resulting in the following sequence of intervals:

1. Both open - correlation cell beam transmitted;
2. C1 closed, C2 open - source blocked;
3. Both closed - neutral density beam transmitted; and
4. C1 open, C2 closed - source blocked.

This sequence repeats about every 6 msec.

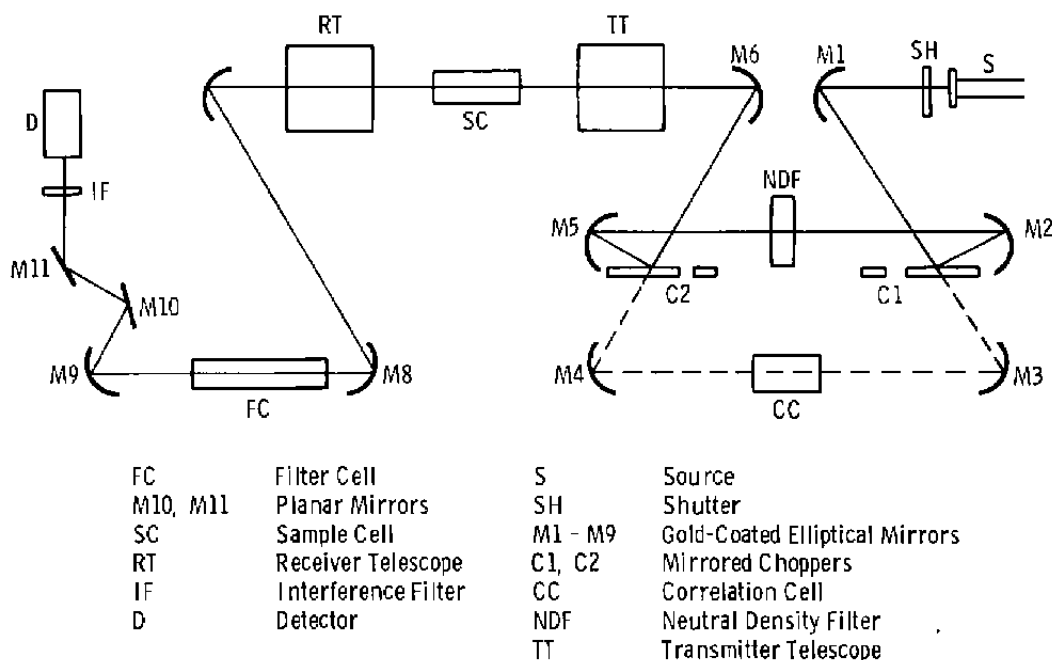


Figure 4. RSGFC spectrometer optical schematic.

The beam is focused by the transmitting telescope (TT) at the center of the plume or calibration sample cell (SC) where the source image is approximately 1 cm in diameter. The receiver telescope (RT), identical to the transmitter telescope, focuses and directs the beam to mirror M7 which directs it to mirror M8 which focuses the beam at the center of the filter cell (FC) mounted in a tube furnace. The filter cell, consisting of a 38-cm-long by 7.5-cm-diam quartz tube body and 7.5-cm-diam by 6-mm-thick calcium fluoride windows, is filled with CO₂ at a pressure of 720 torr and one cc of liquid water before heating. The center 10

cm of the cell is heated to approximately 810 K. The beam emerging from the filter cell is focused by mirror M9 via planar mirrors M10 and M11 on a liquid-nitrogen-cooled indium antimonide detector. An interference filter is mounted at the detector housing entrance window.

The source tube is supplied with low-pressure (1 to 5 torr) CO (99.99-percent purity) after passing through an activated charcoal, glass wool filter. The pressure is monitored downstream of the source. The low pressure and flow are maintained by a 283-l/min-capacity vacuum pump.

The signal from the detector is amplified by a preamplifier and variable gain a-c amplifier. The amplified signal is simultaneously fed into two dual-channel boxcar integrators which provide signal averaging. The boxcars are triggered by a signal from the second chopper. The timing of the boxcars is set to sample at four times during each complete chopper sequence corresponding to the four intervals described previously.

The number of cycles during which the boxcar integrators average is controlled by a sample control panel. The averaged signals are displayed on four digital displays. Control of the data acquisition as well as data recording can be accomplished automatically by the Arnold Engineering Development Center (AEDC) Engine Test Facility (ETF) Technology Data Acquisition System (TDACS) which digitizes the data and displays the averaged signals on a cathode ray tube.

2.2 OPERATING PRINCIPLES

The IR radiation emitted by the CO plasma generated in the source tube by absorption of microwave radiation is a multiline emission consisting of narrow lines ($< 0.06 \text{ cm}^{-1}$) from the fundamental (1-0) band and several hot bands (2-1, 3-2, 4-3, and others). An example of this spectrum is presented in Fig. 5. Because of the nonequilibrium nature of the excitation mechanism, the hot-band intensities are comparable to the fundamental intensity. CO at temperatures of interest to this study, 300 to 2,000 K, is essentially transparent to the source hot-band radiation, particularly the 3-2 and 4-3 band radiation. This radiation is said to be uncorrelated to the CO absorption spectrum. After passing through the correlation cell, essentially all of the radiation corresponding to transitions normally observed in CO in the temperature range of interest is removed; any further attenuation of the beam on passing through a plume or sample cell is attributed to uncorrelated absorption, i.e., particulate and window attenuations and absorptions attributed to other species.

The other beam, the NDF beam, contains both the correlated and uncorrelated radiation and is absorbed by CO in the plume or sample. The difference of the absorption of the two beams is therefore related to the CO content of the sample region.

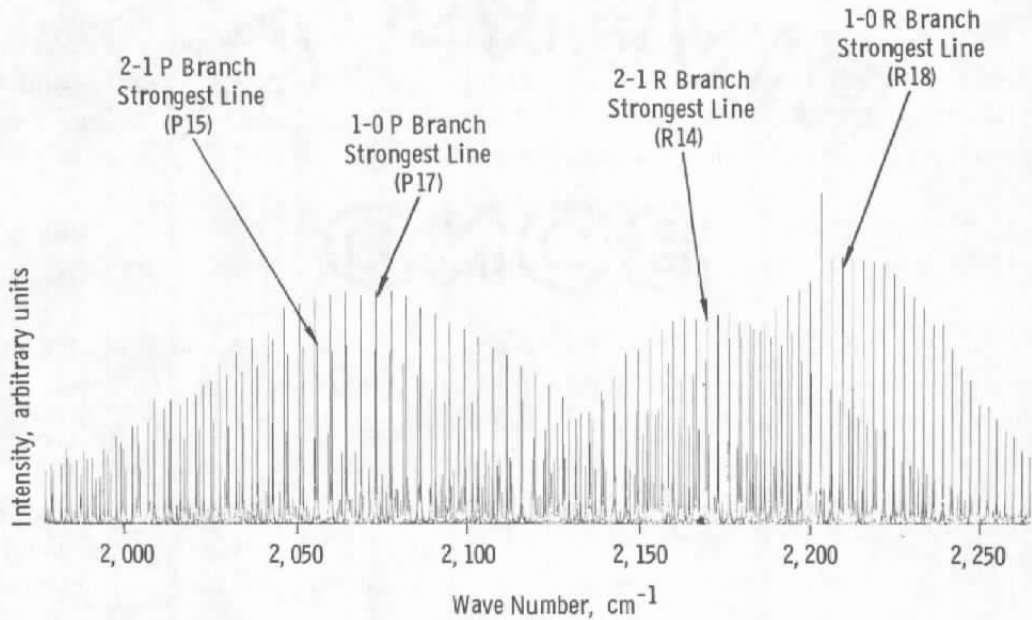


Figure 5. RSGFC spectrometer source spectrum - pressure, 1.32 kPa; input power, 42 w.

The response (R) of the instrument to a sample is defined as follows:

$$R = 1 - \frac{I_{ND} \text{ (sample)}}{I_{ND} \text{ (no sample)}} \times \frac{I_{CC} \text{ (no sample)}}{I_{CC} \text{ (sample)}} \quad (1)$$

where I_{ND} is the neutral density beam intensity and I_{CC} is the correlation cell beam intensity. Both of these intensities are measured with respect to a source-blocked zero. In the limit that the correlation cell beam is not attenuated by the sample, the instrument response reduces to the absorbance of the sample as registered by the neutral density beam.

If the two beams are attenuated by uncorrelated absorptions to the same extent, then the I_{CC} ratio term corrects the I_{ND} ratio for these absorptions; and the instrument response is dependent only on the CO content of the sample or plume.

The two beams, after passing through the sample region, are optically filtered twice before reaching the detector. The first filter, a heated $\text{CO}_2\text{-H}_2\text{O}$ vapor cell, was described previously. The purpose of this cell is twofold:

1. It serves to attenuate source lines coincident with CO_2 and H_2O lines and thus reduces the effects of "accidental" correlations between the CO spectrum and the CO_2 and H_2O spectra (the two principal plume species with spectra overlapping the CO fundamental spectrum (Ref. 8)).
2. It serves to attenuate the possibly noisy plume CO_2 and H_2O emissions and partially replace the plume emissions with less noisy hot-cell emissions.

The second filter, one of two interference filters, is mounted at the detector. This filter limits the spectral response of the instrument to the CO fundamental band and overlapping hot bands. The transmittances of the two filters used are shown in Figs. 6 and 7. The broader pass filter admits most of the CO fundamental band spectra and is designated the CO fundamental filter (Fig. 6). The narrower pass filter admits a large portion of the P branch of the fundamental and is designated the CO P branch filter (Fig. 7). The CO P branch filter was used during the combustor tests because of signal/noise considerations, even though laboratory studies indicated that greater instrument sensitivity to CO was obtained using the CO fundamental filter.

2.3 OPERATING PROCEDURES

Data acquisition is preceded by instrument maintenance and setup procedures. Particular care must be taken to ensure that there are no deposits in the source tube from previous use and that the two beams focus at the same point in front of the transmitting telescope.

Data acquisition consists of recording the accumulated boxcar integrator signals for all four intervals of the chopper timing sequence as described previously. Normally, 2,000 sequences are accumulated in approximately two minutes before recording.

As a check for zero drifts (nonzero signals with grounded input) and amplification drifts of individual channels as well as any synchronous noise, the entire data acquisition sequence is usually repeated with the source blocked by a shutter.

A typical complete measurement sequence is:

1. No sample - shutter open,
2. No sample - shutter closed,
3. Sample in beam - shutter open,
4. Sample in beam - shutter closed,
5. Sample in beam - shutter open,
6. No sample - shutter closed, and
7. No sample - shutter open.

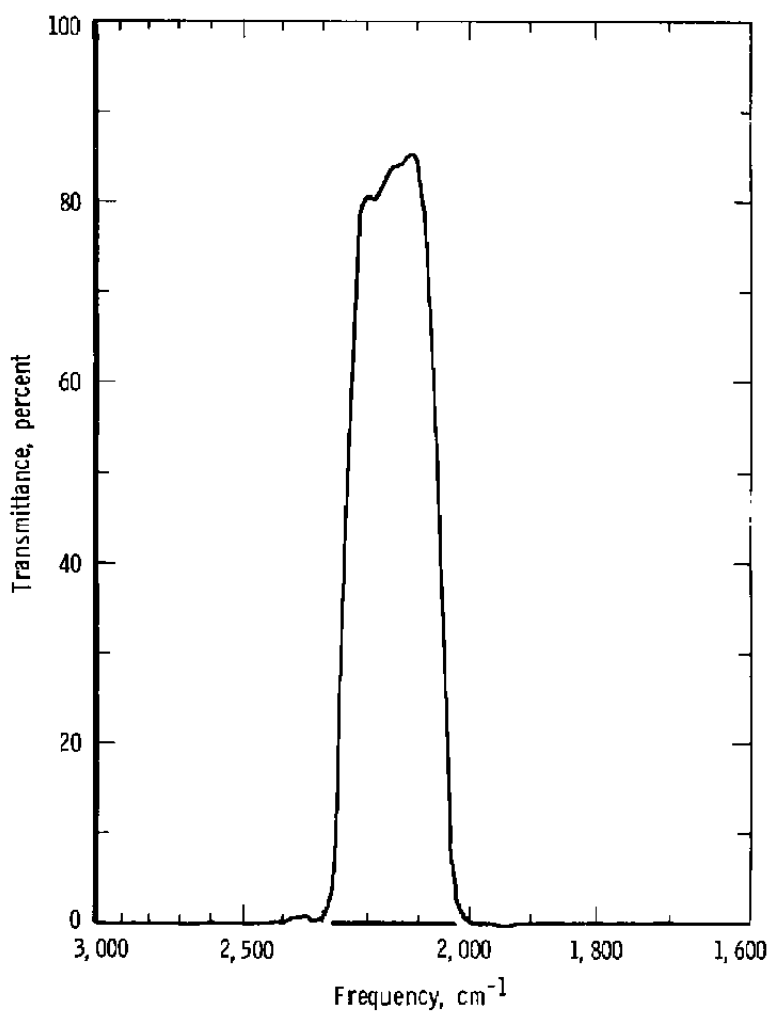


Figure 6. CO fundamental interference filter transmittance plot.

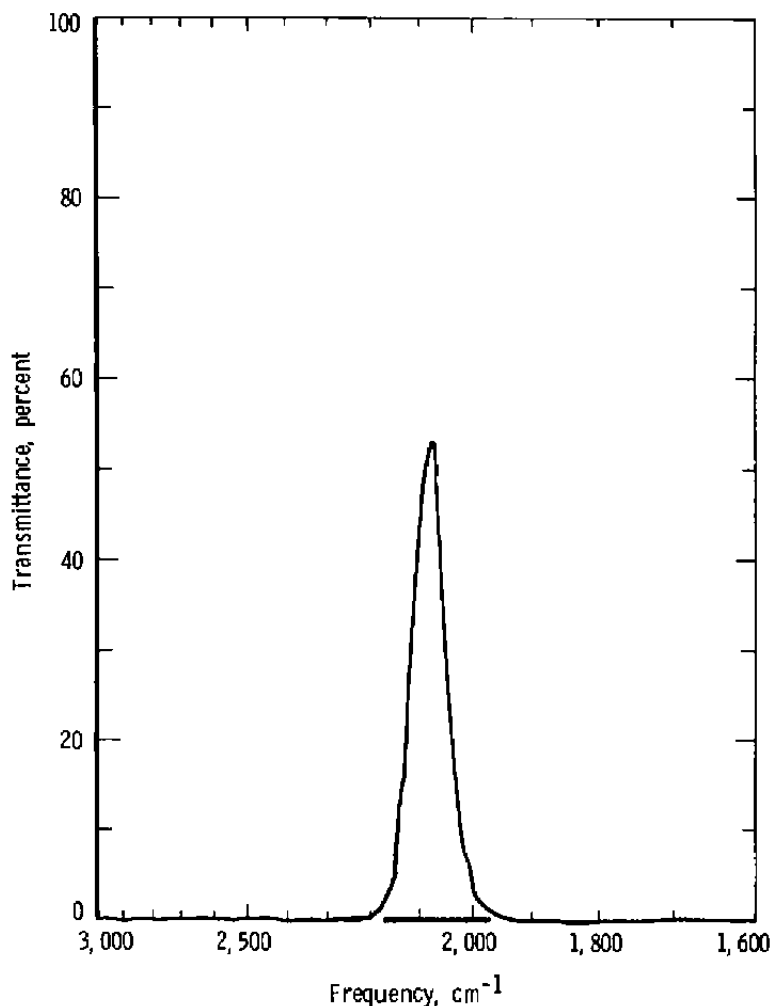


Figure 7. CO P branch interference filter transmittance plot.

At each condition, as many as 20,000 chopper sequences are recorded, i.e., ten partial accumulations of 2,000 sequences. Each partial accumulation can be recorded on magnetic tape by the TDACS system.

3.0 DEVELOPMENT AND CALIBRATION

The instrument was originally developed and calibrated in the ETF R-2G laboratory area and subsequently moved to the ETF Propulsion Research Cell (R-2C-1). After installation in Research Cell R-2C-1, problems arose which necessitated further development and modification of the instrument which ultimately improved the instrument performance.

The laboratory calibration was performed with the instrument equipped with the CO fundamental filter and an unheated filter cell. The source operating conditions were 42 w of microwave input power and 10-torr CO pressure. The instrument optimized for test cell operating conditions was equipped with the CO P branch filter and a heated filter cell. The source was operated at 3.5-w microwave input power and 1.0-torr CO pressure at the test cell. These operating conditions minimized deposit buildup in the source tube and increased the instrument sensitivity of CO. The increased sensitivity to CO is attributed to lower tube operating temperatures and hence lower hot parts continuum emission which effectively dilutes the resonance radiation from the gaseous plasma. The sensitivity of the instrument was approximately doubled when the source was operated at the lower pressure and power conditions.

A study of the effects of sample temperature and pressure on the response of the instrument to CO was performed in the laboratory. It was found that in the temperature range of 300 to 600 K and the pressure range of 48 to 97 kPa the response of the instrument to CO-N₂ mixtures is a function of mainly the CO concentration and the path length, i.e., it is not a function of temperature and only a very weak function of pressure within experimental error. Table 1 presents some results of these calibrations using a 10-cm path-length cell. The very weak dependence of the instrument response with respect to temperature and pressure is qualitatively accounted for by the preliminary model of the instrument response.

Calibration of the instrument at the test cell using a calibration sample cell was also conducted with the instrument optimized for test cell operating conditions. The results of the calibration using both the CO fundamental filter and the CO P branch filter, the filter used during the tests, are presented in Fig. 8. Note that the instrument response of the test cell optimized instrument using the CO fundamental filter is approximately twice that of the laboratory calibration using the same filter (Table 1). Note also that the response of the instrument equipped with the CO P branch filter is approximately 60 percent of the CO fundamental filter equipped instrument response. The CO P branch filter calibration curve was used to reduce the test cell plume data.

4.0 PRELIMINARY MODEL OF THE INSTRUMENT RESPONSE

A simple preliminary model of the instrument response was constructed using the following approximations and assumptions:

1. The relative strengths of the source lines are constant with respect to time and the source operating conditions.

Table 1. RSGFC Spectrometer Laboratory Calibrations

CO Concentration, ppm	Pressure, kPa	Temperature, K	Response, percent ± Standard Deviation
2,980	96.5	300	10.2 ± 0.9
2,980	48.3	300	8.9 (one measurement)
2,980	96.5	400	11.0 ± 0.9
2,980	96.5	505	10.2 ± 0.3
2,980	48.3	505	9.4 ± 0.1
2,980	96.5	603	9.9 ± 0.1
2,980	48.3	603	8.9 ± 0.3
1,000	96.5	300	4.2 ± 0.2
1,000	96.5	505	4.0 ± 0.3
1,000	48.3	505	3.9 ± 0.2
1,000	96.5	603	3.9 (one measurement)
1,000	48.3	603	3.9 (one measurement)
505	96.5	505	1.6 ± 0.2
505	48.3	505	1.8 ± 0.1
505	96.5	603	1.7 ± 0.2
505	48.3	603	1.7 ± 0.3
427	96.5	300	1.6 ± 0.4
427	96.5	400	1.4 ± 0.1

Note: Spectrometer Operating Conditions

Source input power - 42 w

Source pressure - 10 torr

Filter cell temperature - 300 K

Interference filter - CO fundamental filter

- The source radiation as viewed by the instrument has no continuum component.
- The source lines are much narrower than the sample absorption lines.
- The sample absorption lines are describable by a Lorentz absorption shape (Ref. 9).
- Only the $C^{12}O^{16}$ fundamental band is absorbed by the sample.

6. Overlap of sample absorption lines can be ignored.
7. The detector response and the NDF transmittance is constant over the bandpass of the interference filter.
8. The absorption line strengths can be adequately approximated by the Herman-Wallis approximation (Ref. 10) as used by Hanson (Ref. 11) and the fundamental band strength determined by Varanasi and Sarangi (Ref. 12).
9. Pressure broadening is proportional to pressure and is characterized by a temperature dependence of $T^{-0.75}$ (Ref. 12).
10. The CO pressure broadening coefficients of the plume constituents are approximately equal to the N_2 coefficient ($0.06 \text{ cm}^{-1}/\text{atm}$ at 298 K) (Ref. 12).
11. The heated filter cell does not influence the instrument response to CO.

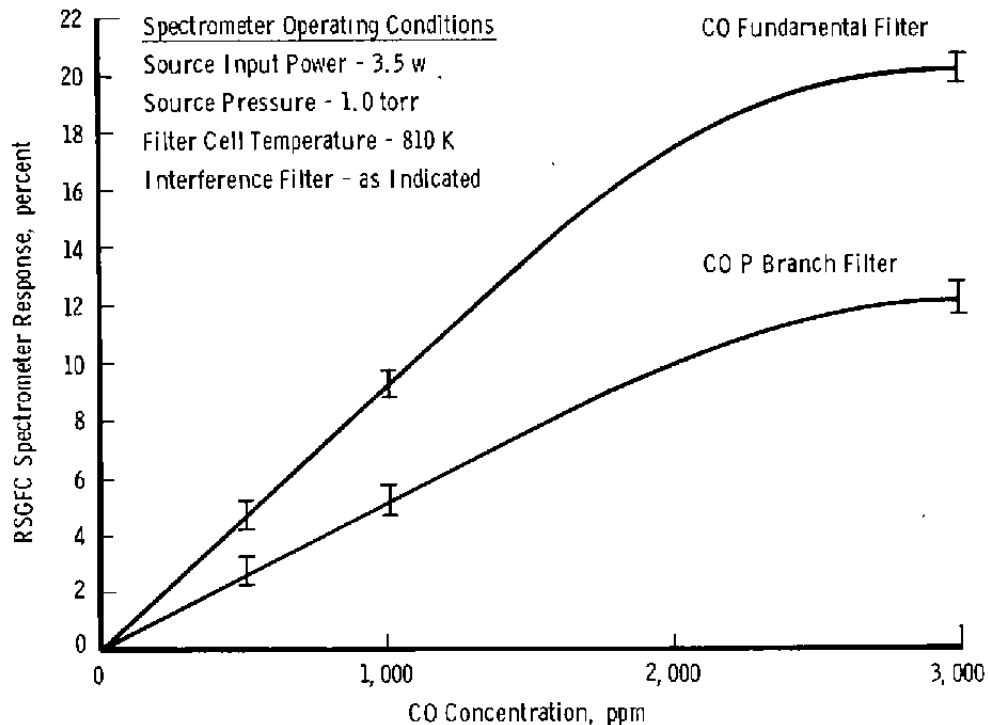


Figure 8. RSGFC spectrometer test cell calibration curve - path-length, 10 cm; temperature, 300 k.

The small pressure dependence of the calibration data (Table 1) is seen to be a consequence of the Lorentz line shape assumption (4), the narrowness of source lines

relative to the absorption line assumption (3), the absence of continuum source radiation assumption (2), and the pressure broadening coefficient pressure proportionality assumption (9). Given these assumptions, the absorption coefficient (k) at the center of a single absorption line is found to be (Ref. 13):

$$k = \frac{S \chi_{CO} L_0}{\gamma^0 \pi} \left(\frac{273.15}{T} \right)^{0.25} \quad (2)$$

where S is the line strength of the absorption line (cm molec^{-1}), L_0 is Loschmidt's constant ($2.69 \times 10^{19} \text{ molec cc}^{-1} \text{ atm}^{-1}$), χ_{CO} is the mole fraction of CO, γ^0 is the pressure broadening coefficient ($\text{cm}^{-1} \text{ atm}^{-1}$), and T is the sample absolute temperature (K). Note that this expression is pressure independent.

The temperature independence can be qualitatively explained by examining Eq. (2). For a given line, k is found to be proportional to $T^{-0.25}$ if the temperature dependence of S is ignored. If a large portion of a band is included in the interference filter bandpass, it is not unreasonable to expect, on the average, that the net result of the individual variations of S will contribute very little to the net temperature dependence of the instrument response. This leaves the $T^{-0.25}$ dependence which represents only approximately a ± 8 -percent variation in the absorption coefficient over the total temperature range of the calibration (300 to 600 K).

The response of the instrument predicted by the model is

$$R = 1 - \left[\frac{\sum_f F_i I_i \exp - \left[\frac{\ell S_i L_0 \chi_{CO}}{\gamma^0 \pi} \left(\frac{273}{T} \right)^{0.25} \right] - \sum_h F_i I_i}{\sum_{f,h} F_i I_i} \right] \quad (3)$$

where F_i is the transmittance of the interference filter at source line i ; I_i is the relative intensity of source line i (arbitrary units); ℓ is the path length (cm); S_i is the line strength of the sample fundamental line absorbing source line i ($\text{cm}^{-1} \text{ molec}^{-1}$); and f,h represent summations over, respectively, the fundamental source lines and the hot-band source lines. The other symbols are defined below Eq. (2).

Numerically, this calculation was performed for the following case:

1. CO concentration - 2,980 ppm in N₂;
2. T - 298 K;
3. P - 101.325 kPa;
4. Path length - 10 cm; and
5. CO fundamental filter bandpass.

The calculation yields an instrument response of 0.185 as compared to the experimental value of 0.202 ± 0.005 (Fig. 8).

Although the agreement between experiment and theory for this case is adequate, more work is needed to validate the model assumptions and to calculate the effect of temperature, pressure, CO concentration, and filter characteristics on the instrument response.

5.0 TEST CELL APPLICATION

Experiments comparing RSGFC spectrometer CO concentration measurements with measurements made with a conventional probe sampling system were conducted in the ETF Research Cell R-2C-1. This cell is equipped with a 14-cm-diam turbine engine combustor with an attached 5.5-cm-diam standard ASME long radius nozzle, a heated combustion air supply, a pressurized JP-4 fuel system, and a test section in which optical and probe sampled emission measurements are made. The details of the test cell and its operation can be found in Ref. 14. A schematic diagram of the test cell is presented in Fig. 9.

The sampling probe used to extract the gas sample from the exhaust stream is a stainless steel expansion-type probe. This probe provides an expansion of the gas sample across an entrance orifice. The pressure differential across the orifice is maintained by a positive displacement pump. All probe measurements were made with the probe inlet located on the exhaust stream centerline at an axial position of 2.3 cm downstream of the nozzle exit plane. The probe was cooled by a closed system containing a mixture of ethylene glycol and water.

The gas samples were analyzed for CO content by a commercial nondispersive infrared CO analyzer calibrated against standard commercial calibration gases.

The spectrometer optical axis was positioned perpendicular to the exhaust flow 2.3 cm downstream of the nozzle exit plane at the plume centerline. The instrument was set up as previously described for optimized test cell performance.

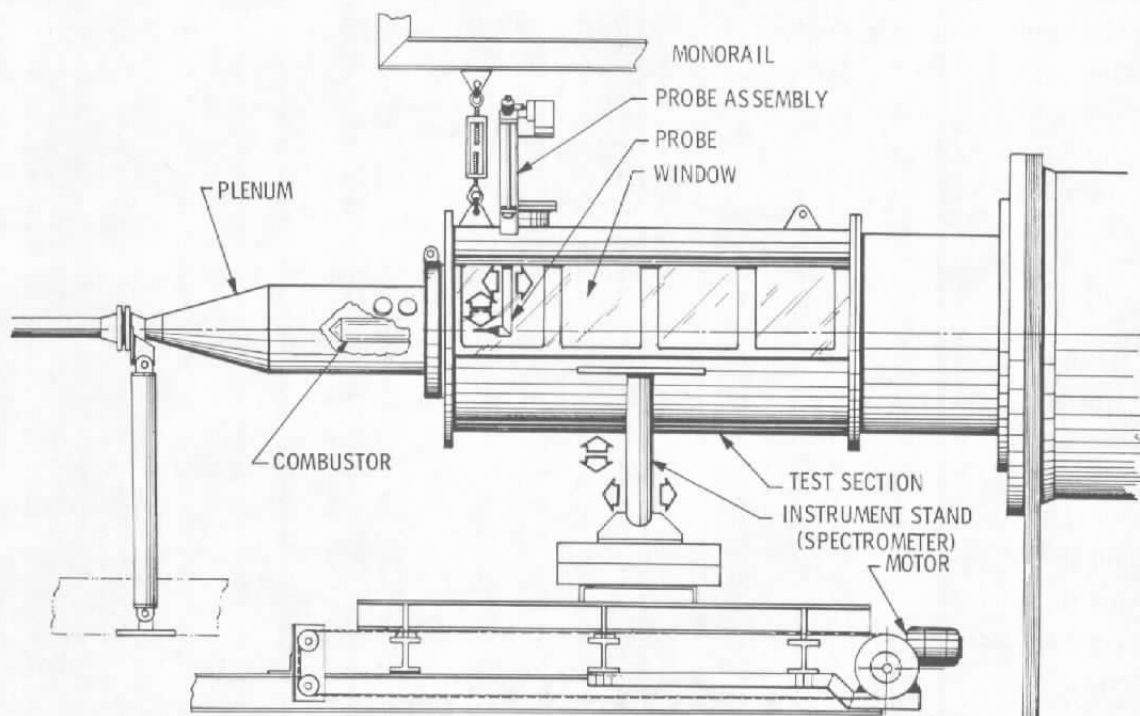


Figure 9. Diagram of Research Cell R-2C-1.

The combustor operating conditions and measurement results are summarized in Table 2. These results represent the average of six measurements. The diameter of the plume at the axial measurement position was 5.0 cm.

Table 2. Test Cell Results

Fuel/Air \pm SD	0.01124 \pm 0.00013
ϕ Static Temperature \pm SD, K	531 \pm 2
ϕ Static Pressure \pm SD, kPa	62.6 \pm 0.4
Probe CO Concentration \pm SD, ppm	1,071 \pm 31
RSGFC Spectrometer CO Concentration \pm SD, ppm	960 \pm 520

The static temperature and pressure were calculated from the isentropic equations relating total to static conditions using the Mach number at the point of measurement determined from a method of characteristics solution of the flow-field equations (Ref. 15). The total temperature was calculated using the method of Ref. 16, and the total pressure in the combustor was measured using a total-pressure probe.

6.0 CONSIDERATIONS FOR FUTURE INSTRUMENT DEVELOPMENT

As indicated in Table 2, the RSGFC spectrometer measurements are in agreement with the probe measurements within experimental error, but the experimental error is unacceptably large (± 54 percent). The principal reason for the large uncertainty is the poor signal-to-noise ratio (S/N). Although precautions were taken to optically filter out the noisy plume radiation, the S/N directly from the detector was only approximately 0.4. With 20,000 boxcar accumulations, the S/N is theoretically increased to 56.6. This corresponds to an instrument response uncertainty of approximately 0.018, which at the instrument response level of the present experiment corresponds to a measurement uncertainty of $+70$ percent.

There are several options available to reduce the experimental uncertainty:

1. Increase the path length using multiple pass optics. This would have the effect of increasing the instrument response for a given CO concentration. It would also be expected to increase the optical noise level somewhat and add to already difficult alignment procedures.
2. Increase the number of boxcar accumulations. Given the instrument response level of the present experiment, a ± 10 -percent experimental uncertainty goal would necessitate 1×10^6 accumulations which would lengthen the time of a single complete measurement to approximately eight hours. Clearly, a faster chopper system would need to be developed.
3. Improve the optical noise filtering. If the optical noise is caused by molecular species emission radiation, an improved filter cell and/or interference filter would be expected to help; but if the noise is spectrally continuous (e.g., particulate radiation), this approach would probably be ineffective.
4. Intensify the source. Development of a more intense source should lead to improved instrument performance by increasing the S/N.

The initial application of the instrument represents a rather severe test because of the relatively noisy optical signal and the short path length. It would appear that unless the S/N can be significantly improved, the current model of the RSGFC spectrometer will only be useful for lower temperature or lower noise flows and/or higher concentration, longer path-length systems.

7.0 SUMMARY AND CONCLUSIONS

The development and testing of a resonance source gas filter correlation spectrometer for CO measurement in high temperature, possibly acoustically and optically noisy combustion systems, are described. The instrument incorporates a microwave-excited low-pressure CO plasma radiation source.

Calibration and preliminary modeling indicate the instrument response to CO is characterized by a very weak function of temperature between 300 and 600 K and of pressure between 48 and 96 kPa.

A preliminary field test of the instrument behind a jet combustor revealed severe optical noise interference. The CO concentration of the plume, as determined by the instrument, was found to be 960 ± 520 ppm as compared to $1,071 \pm 31$ as determined by an orifice probe, gas analyzer measurement. It is concluded that improved instrument performance is dependent upon improving the signal-to-noise ratio. If this is not possible, the instrument's usefulness will be limited to low temperature, low noise or high concentration, long path-length systems.

REFERENCES

1. Few, J. D., Bryson, R. J., and McGregor, W. K. "Evaluation of Probe Sampling versus Optical In Situ Measurements of Nitric Oxide Concentrations in a Jet Engine Combustor Exhaust." AEDC-TR-76-180 (ADA034726), January 1977.
2. Benson, R. and Samuelsen, G. S. "Oxides of Nitrogen Transformation While Sampling Combustion Products Containing Carbon Monoxide, Hydrogen and Hydrocarbons." Presented at the 1977 Spring Meeting, Western States Section, Combustion Institute, University of Washington, Seattle, April 18-19, 1977.
3. Burch, D. E. and Pembroke, J. D. "Instrument to Monitor CH₄, CO and CO₂ in Auto Exhaust." EPA Report 650/2-73-030, October 1973.

4. Gryvnak, D. A. and Burch, D. E. "Monitoring NO and CO in Aircraft Jet Exhausts by a Gas-Filter Correlation Technique." AFAPL-75-101, January 1976.
5. Herget, W. F., Jahnke, J. A., Burch, D. E., and Gryvnak, D. A. "Infrared Gas-Filter Correlation Instrument for In Situ Measurement of Gaseous Pollutant Concentrations." *Applied Optics*, Vol. 15, May 1976, pp. 1222-1228.
6. Ludwig, C. B., Griggs, M., Malkmus, W., and Bartle, E. R. "Air Pollution Measurements from Satellites." NASA CR-2324, 1973.
7. Bartle, E. R. and Hall, G. "Airborne HCl-CO Sensing System." NASA CR-145095, 1977.
8. Lindquist, G. H., Arnold C. B., and Spellicy, R. L. "Atmospheric Absorption Applied to Plume Emission, Experimental and Analytical Investigations of Hot Gas Emissions Attenuated by Cold Gases." AFRPL-TR-75-30 (ADA015075), August 1975.
9. Mitchell, A. C. G. and Zemansky, M. W. "*Resonance Radiation and Excited Atoms.*" The MacMillan Company, New York, 1934.
10. Herman, R. and Wallis, R. F. "Influence of Vibration-Rotation Interaction on Line Intensities in Vibration-Rotation Bands of Diatomic Molecules." *The Journal of Chemical Physics*, Vol. 23, April 1955, pp. 637-646.
11. Hanson, R. K. "Combustion Gas Measurements Using Tunable Laser Absorption Spectroscopy." Proceedings of the 17th Aerospace Sciences Meeting, New Orleans, Louisiana, January 15-17, 1979.
12. Varanasi, P. and Sarangi, S. "Measurements of Intensities and Nitrogen Broadened Line Widths in the CO Fundamental at Low Temperatures." *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 15, June 1975, pp. 473-482.
13. Young, L. A. "CO Infrared Spectra." *Journal of Quantitative Spectroscopy and Radiative Transfer*, Vol. 8, February 1968, pp. 693-716.
14. Few, J. D., Bryson, R. J., and Lowry, H. S., III. "Optical In Situ versus Probe Measurements of Nitric Oxide Concentration as a Function of Axial Position in a Combustor Exhaust." AEDC-TR-78-32 (ADA067329), March 1979.

15. "User Manual - Description of a Digital Computer Program for Nozzle and Plume Analysis by Method of Characteristics." TM-54-20-108, Lockheed Missile and Space Company, Sunnyvale, California, December 1966.
16. Osgerby, I. T. and Rhodes, R. P. "An Efficient Numerical Method for the Calculation of Chemical Equilibrium in the H/C/O/N/A System." AEDC-TR-71-256 (AD741825), April 1972.